A study of the Au/Ni ohmic contact on *p*-GaN

D. Qiao,[a] L. S. Yu, and S. S. Lau
ECE Department, University of California, San Diego, La Jolla, California 92093

J. Y. Lin and H. X. Jiang
Department of Physics, Kansa State University, Manhattan, Kansas 66506

T. E. Haynes
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

The formation mechanism of the ohmic Au/Ni/*p*-GaN contact has been investigated. We found that it is essential to (i) deposit a structure of Au and Ni in the proper deposition sequence, and (ii) anneal the bilayer structure in an oxygen containing ambient. Our findings indicated that oxygen assists the layer-reversal reactions of the metallized layers to form a structure of NiO/Au/*p*-GaN. The presence of oxygen during annealing appears to increase the conductivity of the *p*-GaN. It is further suggested that Ni removes or reduces the surface contamination of the GaN sample before or during layer reversal. In the final contact structure, an Au layer, which has a large work function, is in contact with the *p*-GaN substrate. The presence of Au in the entire contacting layer improves the conductivity of the contact. An ohmic formation mechanism based on our experimental results is proposed and discussed in this work. © *2000 American Institute of Physics.*
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I. INTRODUCTION

GaN has been extensively investigated for electronic and optoelectronic applications.[1,2] For light emitting diodes (LEDs) and laser diodes (LDs), the fabrication of low resistance contacts to *p*-type layers is a rather challenging task. It has been reported in the literature that Au/Ni based bilayer structures annealed in an oxygen containing ambient are capable of forming ohmic contacts to *p*-GaN with a contact resistivity in the range of 10^{-2} to 10^{-6} Ω cm^2.[3-7] Two leading models rationalizing the ohmic forming behavior have been proposed. Ho *et al.* suggested that the ohmic behavior was a result of a thin Schottky barrier with a small barrier height, caused by band lineup between NiO and *p*-GaN. The final contact structure resulting from the annealing in air was Au/*p*-NiO/*p*-GaN, where NiO was considered as a *p*-type semiconductor in direct contact with the *p*-GaN layer.[4-6] Koide *et al.* on the other hand, proposed that the ohmic behavior was due to the increase of hole concentration in the near surface region, caused by the removal of hydrogen atoms in the presence of oxygen.[7] The same research group also reported that a structure consisting of Au/sputter-deposited NiO/*p*-GaN did not lead to ohmic contacts.[8] Intentional doping of the sputter-deposited NiO with Li (believed to be a *p*-type dopant in NiO[9,10]) did not improve the contact. Based on this observation, it was concluded that NiO was not the reason for the Au/Ni metallization to yield ohmic behavior.

The objective of this work was to investigate the Au/Ni contact scheme systematically in an attempt to shed light on the mechanism(s) of the ohmic forming behavior.

[a] Electronic mail: dqiao@ucsd.edu

II. EXPERIMENT

The GaN samples were grown on sapphire using metalorganic chemical vapor deposition (MOCVD). The Mg-doped layer was about 1.5 μm in thickness, with a hole concentration of 1.2×10^{17} cm^3 and a mobility of 10 cm^2/V s. For electrical measurements, the circular transmission line method (CTLM) was used to obtain the contact resistivity. Two concentric metallized rings with a gap of 14 μm were used to measure the current–voltage (*I–V*) characteristics. The samples were first cleaned in organic solvents followed by forming CTLM patterns using photolithography. The samples were then etched in a HCl:HF:H$_2$O (1:1:2) solution for 8 s before loading into an e-beam evaporation chamber equipped with dry pumps with a chamber base line pressure of $\sim 10^{-8}$ Torr. Ni and then Au layers were deposited onto the samples at a rate of ~ 3 Å/s and at a pressure of $\sim 3 \times 10^{-7}$ Torr. The metallized CTLM patterns were formed using the lift-off process. Five different metallization structures were used in this study (see Fig. 1). Structure A consisted of a layer configuration of Au(200 Å)/Ni(200 Å)/*p*-GaN. Structure B consisted of 500 Å of Ni on *p*-GaN. In structure C, a single layer of Ni with a thickness of 200 Å was first deposited on *p*-GaN, followed by annealing in vacuum ($\sim 3 \times 10^{-6}$ Torr) at 500 °C for 5 min; after annealing, a layer of Au (200 Å) was deposited on the vacuum-annealed Ni. Structure D consisted of 500 Å of Au on *p*-GaN. In structure E, a single layer of Ni with a thickness of 5, 20, or 50 Å was first deposited on *p*-GaN, followed by annealing in air at 500 °C for 5 min; after annealing, a layer of Au (500 Å) was deposited on the air-annealed Ni. The *I–V* characteristics of the samples were measured on a probe station at various stages of annealing. The probes were made of W with blunted tips to avoid damaging the metal contacts.
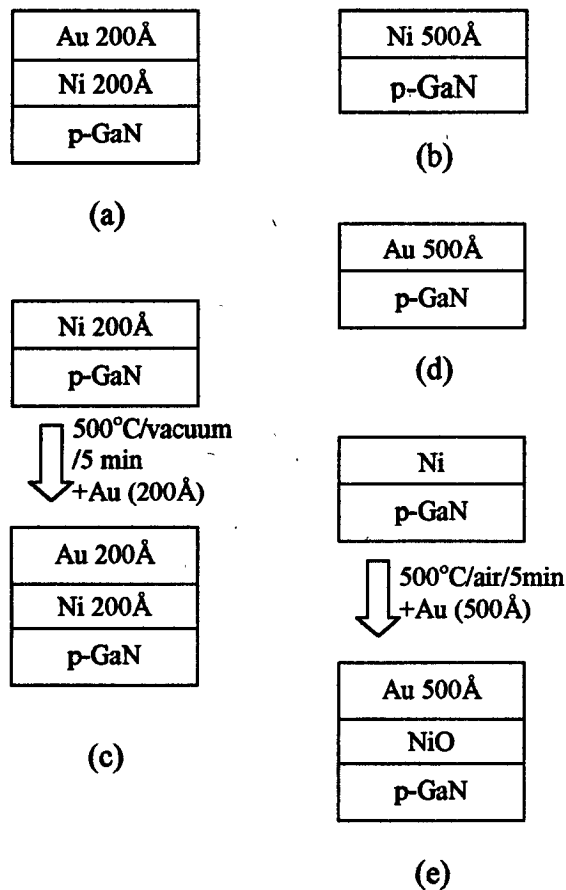
FIG. 1. Metallization structures used in the experiment. (a) Au(200 Å)/Ni(200 Å)/p-GaN, (b) Ni(500 Å), (c) Ni(200 Å), annealing in vacuum at 500 °C for 5 min followed by Au(200 Å) deposition, (d) Au(500 Å), and (e) Au(500 Å)/NiO/p-GaN. The NiO was formed by annealing a layer of Ni (5, 20, and 50 Å) in air at 500 °C for 5 min.

FIG. 2. Typical I–V curves of samples with structure Au(200 Å)/Ni(200 Å)/p-GaN before and after annealing in vacuum or air at 500 °C for 5 min.

Various amounts of pressure were applied to the probes during measurement to ensure reproducibility. MeV He ion Rutherford backscattering spectrometry (RBS) was used to study the metal thin film reactions.

III. RESULTS AND DISCUSSION

In our study we investigated four issues pertinent to the Au/Ni/p-GaN contact to elucidate the ohmic contact forming mechanism. These four issues were: (i) is oxygen necessary in the annealing ambient, (ii) is NiO needed in this contact, (iii) is Au needed, and (iv) is NiO critical to the contact in accordance with the band lineup model?[4] Figure 2 shows the I–V characteristics of the samples consisted of a structure of a Au(200 Å)/Ni(200 Å)/p-GaN (structure A) annealed in air and vacuum. The sample annealed in air at 500 °C for 5 min showed a linear I–V behavior with a contact resistivity, ρ_s, of ~2×10^{-4} Ω cm^2. The sample annealed in vacuum did not show a linear I–V curve. These results indicated that oxygen is necessary for the formation of Au/Ni/p-GaN ohmic contact.

Figure 3 shows the I–V curves of the samples with a single layer of Ni (structure B). It is seen that annealing the samples in vacuum or in air did not lead to linear I–V behavior. However, the sample annealed in vacuum first, fol-
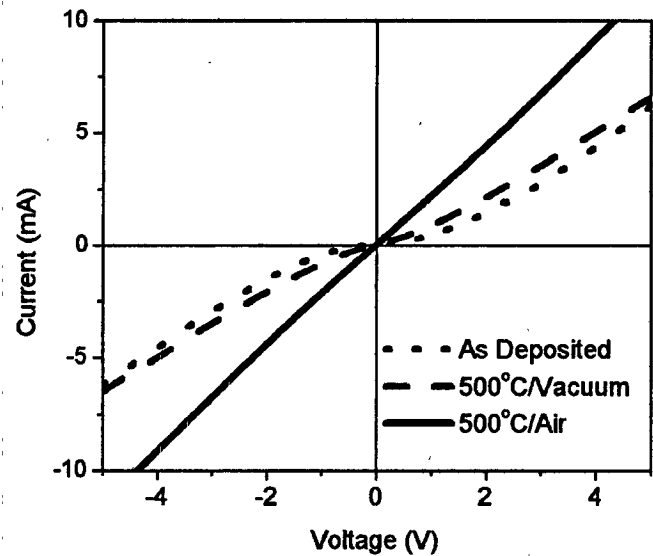
lowed by the deposition of Au and annealed in air at 500 °C (structure C in Fig. 1) yielded a much more linear I–V curve (solid line in Fig. 3) and a much smaller resistance compared to other samples in the same figure.

Figure 4 shows the I–V curve for the sample with a single layer of Au (structure D). Annealing in air did not yield a linear I–V behavior.

The results shown in Figs. 2–4 indicated that the proper deposition sequence and annealing in air are the necessary conditions for the ohmic behavior. Rutherford backscattering spectrometry was used to study the thin film reactions. Figure 5 shows the RBS spectra for the sample with structure A (Au/Ni/p-GaN) before and after annealing in air. Before
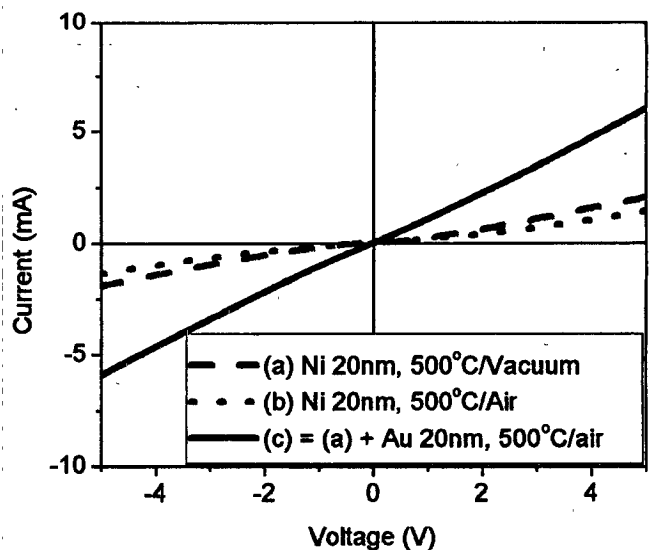
FIG. 3. Typical I–V curves of p-GaN samples (a) with contacts of Ni(200 Å), annealing in vacuum at 500 °C for 5 min, (b) with contacts of Ni(200 Å), annealing in air at 500 °C for 5 min, and (c) with contacts of Ni(200 Å), annealing in vacuum at 500 °C for 5 min followed by Au(200 Å) deposition and then annealed in air at 500 °C for 5 min.
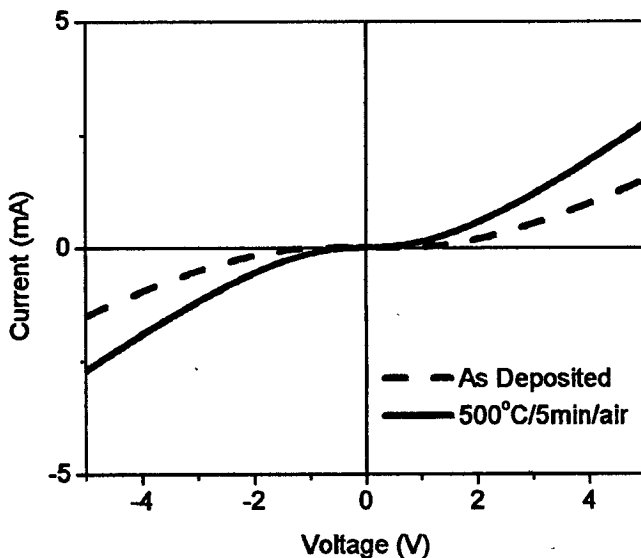
FIG. 4. Typical $I-V$ curves of p-GaN samples with Au(500 Å) before and after annealing in air at 500 °C for 5 min.

FIG. 6. Typical $I-V$ curves of p-GaN samples with a structure of Au(500 Å)/NiO/p-GaN. The NiO was formed by annealing a layer of Ni(5, 20, and 50 Å) in air at 500 °C for 5 min.

annealing, Ni was in contact with the p-GaN with a layer of Au on top. After annealing in air at 500 °C for 5 min, Au was displaced from the surface of the sample to a deeper region. A layer of NiO was formed on the surface. The spreading of Au and Ni signals indicated that the NiO layer on top and the Au layer at the bottom were not uniform in thickness. Au was not observed on the sample surface after annealing within the detection limit of RBS. Computer simulations (using RUMP) of the RBS spectra obtained on the annealed samples suggested that the contacting layer was a mixture of Au–Ni–Ga–O. The results obtained by RBS indicated layer reversal after annealing in agreement with the results reported in the literature.[6] Chen *et al.* investigated the microstructure of the Au/Ni contact on GaN annealed in air using transmission electron microscope.[6] It was found that the con-
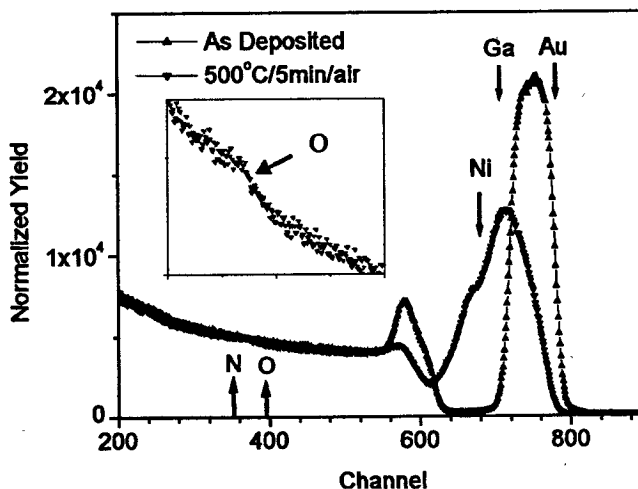

FIG. 5. Rutherford backscattering spectra for the samples with a contact of Au(200 Å)/Ni(200 Å)/p-GaN before and after annealing in air. The arrows indicate the surface energy positions of the elements. The insert shows the O signal of the sample after annealing. The scattering angle was 110° and the angle between the sample normal and the analyzing beam (He$^+$ at 1 MeV) was 3°.
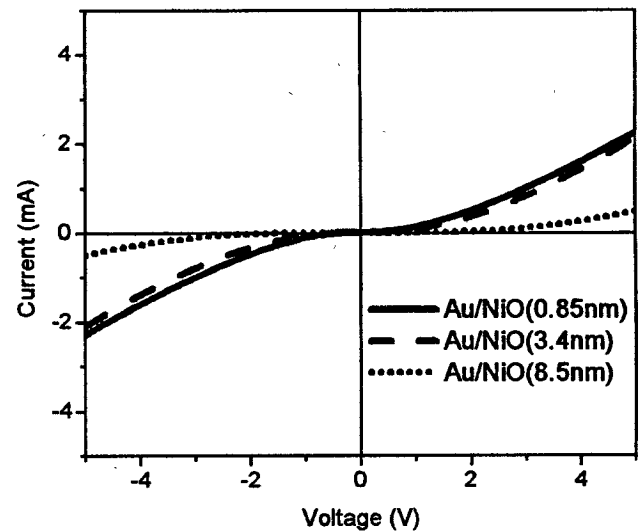
tacting layer consisted of a mixture of NiO embedded with Au-rich and Ni–Ga–O islands. The upper part of the resulting metallized structure was a continuous NiO layer. Their observation also indicated that a layer reversal reaction has taken place during the annealing in air.

It was of great interest to test if a simple structure of Au/NiO/p-GaN could lead to ohmic behavior, as suggested by the band lineup model.[4] To examine this idea, samples with structure E were used. Figure 6 shows the $I-V$ characteristics of the samples with the structure of Au/NiO/p-GaN with various NiO layer thicknesses (8.5, 34, and 85 Å, estimated from the oxidation of Ni with 5, 20, and 50 Å in thickness). It is clear that samples with structure E did not show linear $I-V$ behavior. Furthermore, the current at a given voltage decreased with increasing NiO layer thickness. The results shown in Fig. 6 do not support the ohmic formation mechanism due to a favorable band lineup of the Au/-p-NiO/p-GaN structure.[4]

The role of hydrogen in p-GaN has been extensively studied.[7,8,11–16] It was found that hydrogen passivates Mg as p-type dopant in GaN, thus reducing the hole concentration. Koide *et al.* showed the resistivity of p-GaN was reduced when annealed at 500 °C in oxygen containing ambient, believed to be a result of the removal of H in the sample due to the formation of H_2O near the surface.[7,11] Using secondary ion mass spectroscope, Hull *et al.* also observed the reduction of hydrogen in p-GaN annealed at 600 °C in O_2 containing ambient.[16] This observation is consistent with the theoretically estimated dissociation temperature of the Mg–H complex at ~300 °C, and that a higher temperature is needed to migrate and desorb H from the surface.[13] In our experiment, we found that annealing the Au/Ni contact in air led to ohmic behavior, but not in vacuum (see Fig. 2). The sheet resistance of the sample annealed in air also showed a factor of two reduction as compared to that annealed in vacuum. This result is consistent with the notion that oxygen is effective in removing H from GaN at temperatures as low
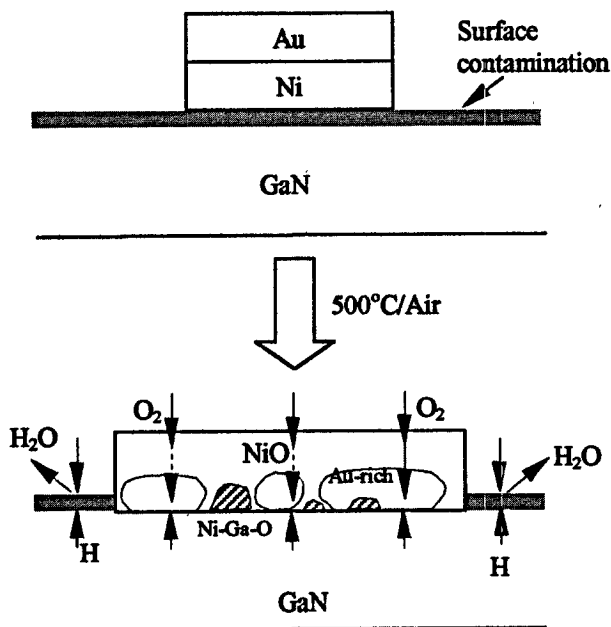
FIG. 7. Schematics of the proposed mechanism of ohmic forming behavior for Au/Ni/p-GaN. The upper figure shows the sample before annealing. The lower figure shows the surface and the suggested reactions as a result of annealing in air.

as 500 °C.[7] This reduction in sheet resistance should lead to higher hole concentrations and facilitate ohmic behavior. However, the reduction of H concentration alone did not lead to ohmic behavior, as shown by the results obtained on air-annealed sample D which consisted of a single layer of Au on GaN (see Fig. 4).

It is well known that a surface contamination layer increases the barrier height at the metal/semiconductor interface.[17–22] The removal of the surface contamination layer would lead to an improved ohmic behavior. Ni has been found to react with GaN at temperatures as low as 500 °C.[3,6,22] Therefore, the reaction between Ni and GaN at ~500 °C can help to reduce the surface contamination layer during annealing. During interfacial reactions in the presence of oxygen, H in GaN beneath the Ni layer is expected to decrease as the interfacial reaction proceeds. The removal of a surface contamination layer and the reduction of H in GaN are important in forming a good ohmic contact. Annealing the Au/Ni contact in air accomplishes both.

Based on the results obtained in this study, we proposed the following mechanism for the ohmic behavior of the Au/Ni contact on p-GaN (see Fig. 7). The as-deposited Au/Ni sample consists of a thin contamination layer on the surface (upper sketch in Fig. 7). As annealing proceeds in air, Ni and Au start to react to form a solid solution. At about 500 °C, several reactions take place: (i) oxygen reacts with hydrogen in GaN not covered by the metal contact pads to form H_2O, thus increasing the hole concentration in the near surface region, (ii) Ni reacts with GaN near the interface and reduces or removes the contamination layer, (iii) Ni reacts with oxygen to form NiO, resulting in the layer reversal with Au in direct contact with GaN, (iv) oxygen removes H underneath the metal contact and increases the hole concentration underneath the contact. As a result of all these reactions,

the contact resistance is greatly reduced. In brief, three important reactions enhance the reduction of contact resistance of Au/Ni contact on p-GaN: the removal of the surface contamination layer, the removal of hydrogen, and the layer reversal of Au/Ni layers. The final contacting metal on p-GaN is Au which has a large work function. The metal/GaN interface is cleaned by the Ni–GaN reactions, and the hydrogen concentration in GaN is reduced by annealing in air.

IV. SUMMARY

In summary, the mechanism of ohmic forming behavior of the Au/Ni/p-GaN contact has been investigated. We found that it is essential to (i) form a structure of Au and Ni in the proper deposition sequence, and (ii) anneal the bilayer structure in an oxygen containing ambient. Our findings indicated that oxygen assists the layer reversal reactions of the metallized layers to form a structure of NiO/Au/p-GaN, and the presence of oxygen appears to cause the increase of the conductivity of the p-GaN. It is further suggested that Ni removes or reduces the surface contamination of the GaN sample before or during layer reversal. In the final contact structure, the Au layer with a large work function is in contact with the p-GaN substrate, and the presence of Au throughout the entire metallized layer improves the conductivity of the contact. Our experimental results do not support the notion of a favorable band lineup of the Au/p-NiO/p-GaN structure resulting in ohmic behaviors.

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